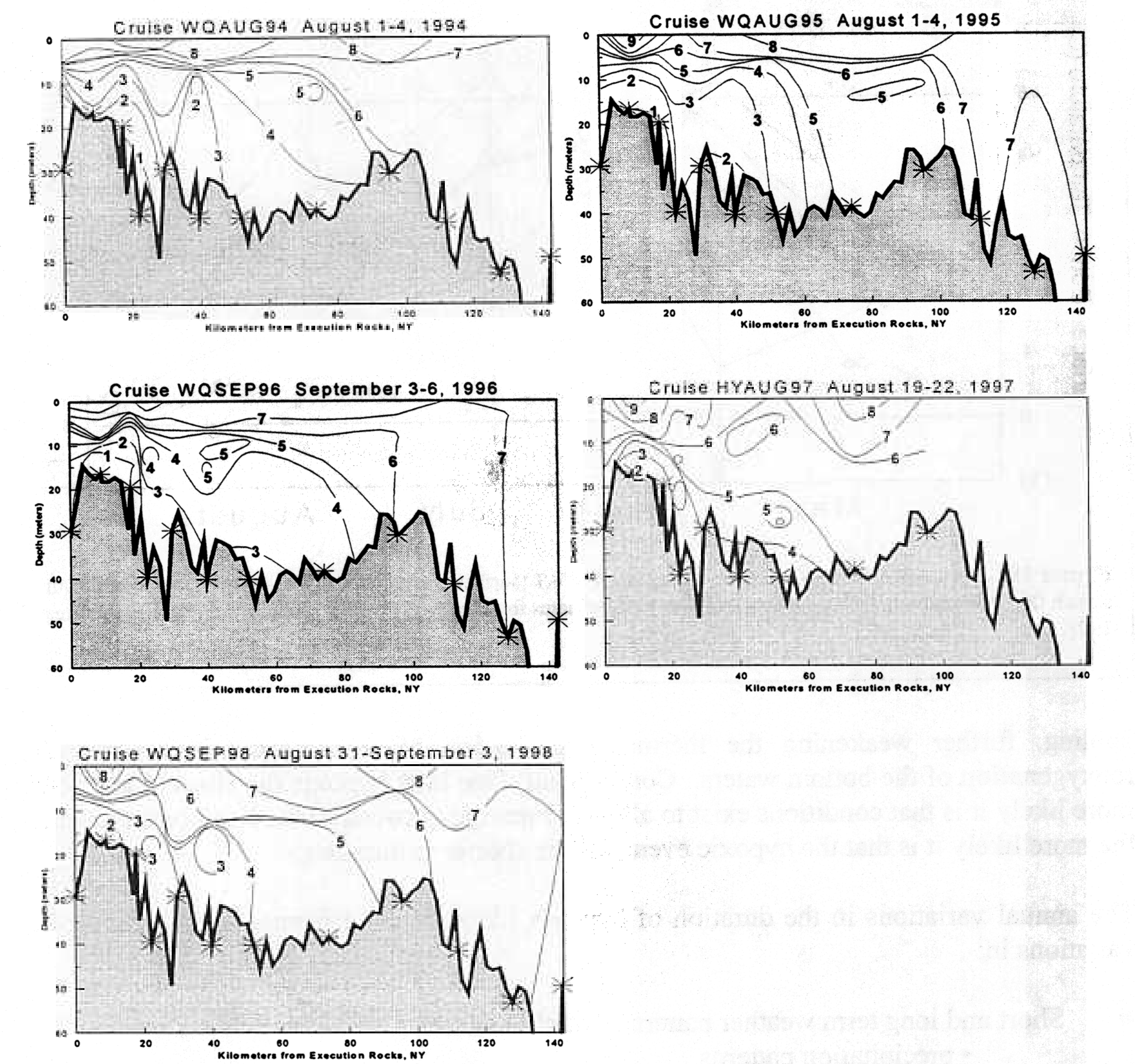

Figure 15. Dissolved oxygen distribution from west to east (Execution Rocks, Station A4 to Fisher's Island/The Race, Station M3) along the deep water axial transect through Long Island Sound during the peak hypoxic event of each of the years 1994 through 1998. "*" indicates location of stations for which data are plotted.

Some physical factors that influence thermocline strength at particular stations include:

- station depth
- location in LIS
- surrounding bathymetry
- circulation patterns of LIS

Stratification is generally at its strongest during June or the early part of July (Figure 16). As the summer progresses, stratification weakens so that it becomes easier for mixing to occur between surface and bottom waters. The arrival of cooler, autumn weather brings about surface water

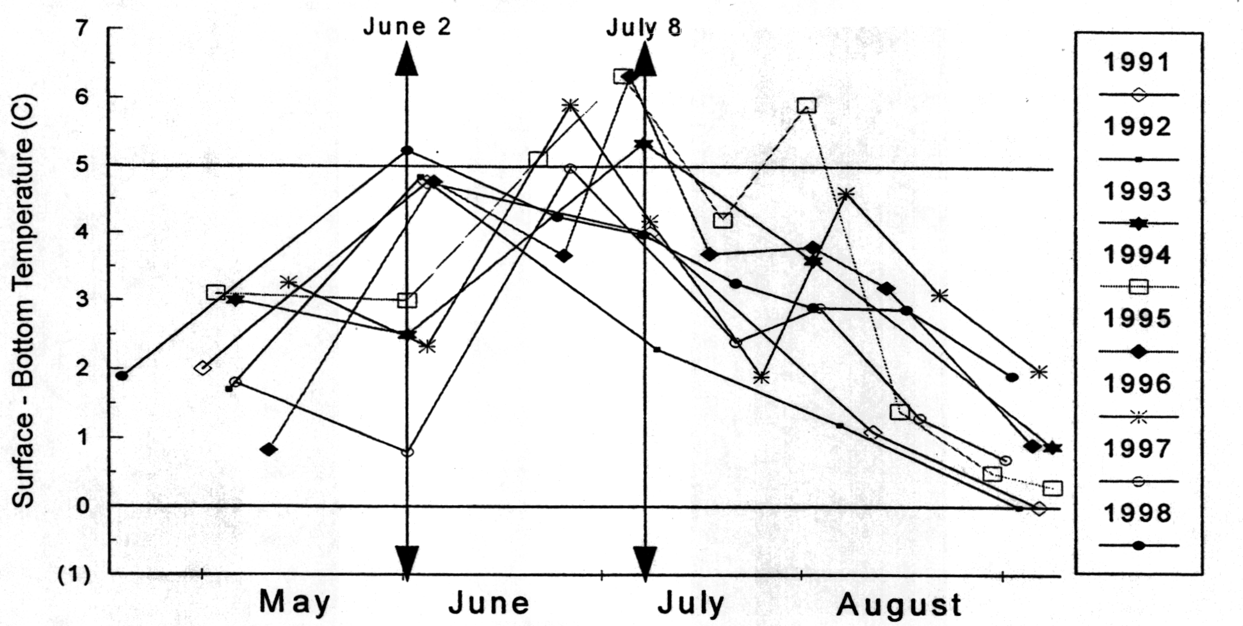

Figure 16. Time series (April 18 through September 9) of ∆T (surface water temperature – bottom water temperature) at station D3, 1991 through 1998. Arrows show the range of dates for ∆Tmax, the earliest, June 2, in 1998, and the latest, July 8, in 1993.

cooling, further weakening the thermal stratification of the water column and allowing reoxygenation of the bottom waters. Consequently, the later hypoxia develops in the Sound, the more likely it is that conditions exist to allow for mixing between surface and bottom waters, and the more likely it is that the hypoxic event will be shorter in duration.

The annual variations in the duration of hypoxia likely resulted from a combination of annual variations in:

- Short and long term weather patterns, which include:
  - precipitation patterns
  - wind events
- Phytoplankton blooms
- Nutrient loading
- Nutrient cycling and recycling
- Other natural and anthropogenic influences

Station D3

Station D3 is located in the eastern-most and the deepest portion of the Narrows. Station D3 does not experience hypoxia every year. The station is used as an example to show how stratification and the development of hypoxia in the Sound relate. Figure 17 shows a time series of the surface minus bottom water temperature (∆T) at station D3 for the years 1991 - 1998. The seasonal pattern of ∆T is clear. The largest ∆T (∆Tmax) occurred in the early summer when rapid

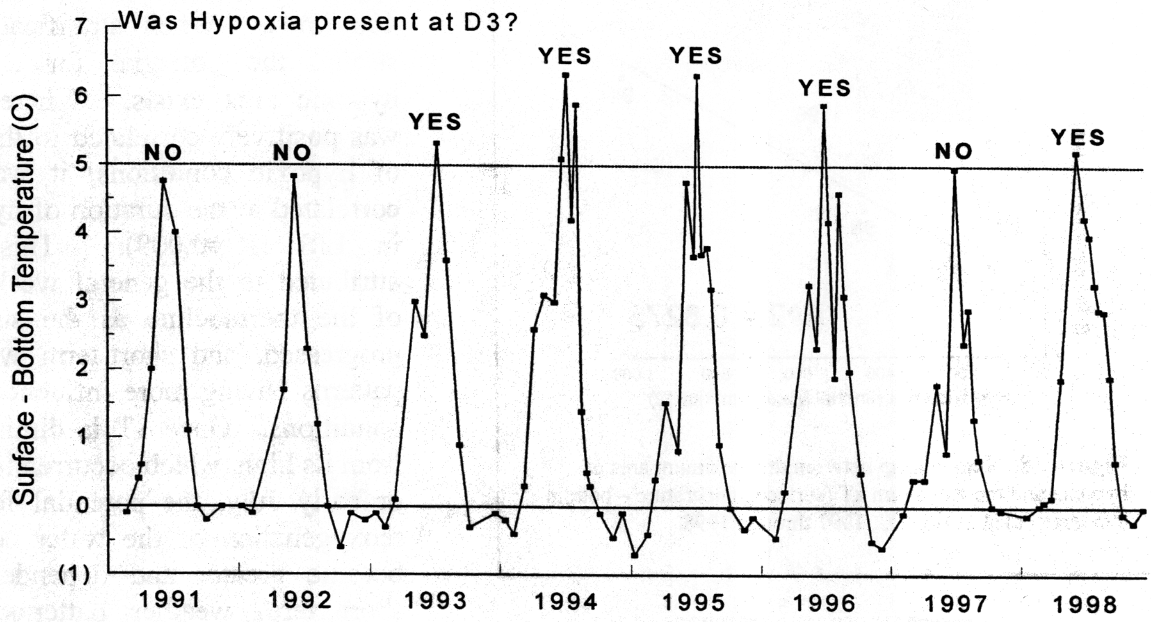

Figure 17. Time series of ΔT (surface water temperature – bottom water temperature) at station D3, 1991 through 1998.

surface water warming exceeded the rate of warming in the bottom waters. The smallest ΔT occurred during the winter when bottom waters were actually warmer than the surface (negative ΔT) (Figure 17).

The years when station D3 became hypoxic (1993-1996 and 1998) coincided with the largest observed values of ΔT (Figure 17). In each case, the observed maximum ΔT was greater than 5.0 degrees C. The timing of the maximum ΔT varied annually, occurring from early June to early July (Figure 16).

The maximum area of hypoxia was related to the strength of the thermocline. There was a positive correlation (R^2=0.8275) between the maximum ΔT observed at station D3 and the maximum area of hypoxia in the same year (Figure 18). Maximum ΔT and the maximum area of hypoxia never occurred at the same time during the 1991-1998 period.

A positive relationship also existed between ΔTmax and the maximum area of hypoxia when the maximum ΔT from other stations were used (e.g. Station B3, R^2=0.36; Station F3, R^2=0.41), but none exhibited as strong a correlation as that when the data from Station D3 were used. Just why conditions at D3 should be so suggestive of the eventual hypoxic event throughout the Sound is not known, although it is likely a function of the station's location and its physical characteristics.

Conditions at Station D3 appeared helpful in characterizing the magnitude of hypoxia for each year. In general, when D3 was not affected by hypoxia the area of hypoxia in that year was smaller (less than 350 km^2), and if D3 was hypoxic ('93, '94, '95, '96 and '98) the extent of

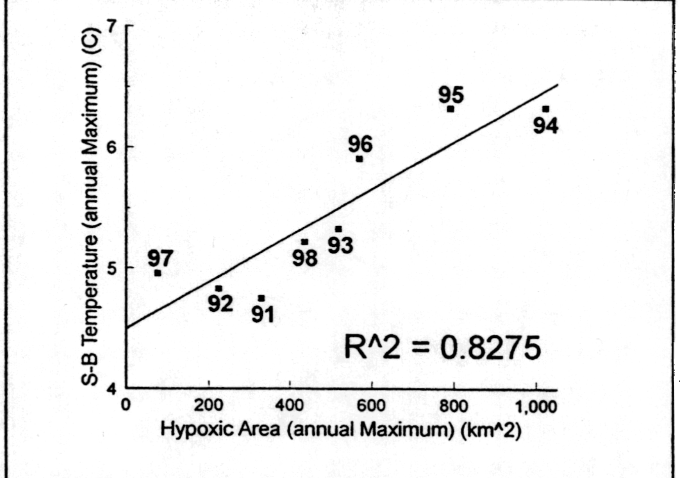

Figure 18. Relationship between the maximum area of hypoxia and the maximum ΔT (surface temperature – bottom temperature) at station D3, 1991 through 1998.

hypoxia was substantial (greater than 400 km^2). When stratification is strong, the potential for a large hypoxic area exists. Whereas ΔT was positively correlated to the area of hypoxic conditions, it was not correlated to the duration of hypoxia in LIS (R^2=0.009). This was attributed to the general weakening of the thermocline as the summer progressed, and short-term weather patterns having more influence over conditions. Once ΔT is diminished from its high, which occurred in June or early July, the potential for the reoxygenation of the water column became greater and dependent on short term weather patterns. A strong wind event could more easily transport oxygen from the surface waters into the water column because the thermal barrier that would prevent mixing was weakening.

Trend Analyses

The results of trend analyses indicated that five stations had a significant increasing trend ($p<0.05$) over the five-year period of 1994-1998 (Figure 19 and Table 8). Thirty-three additional

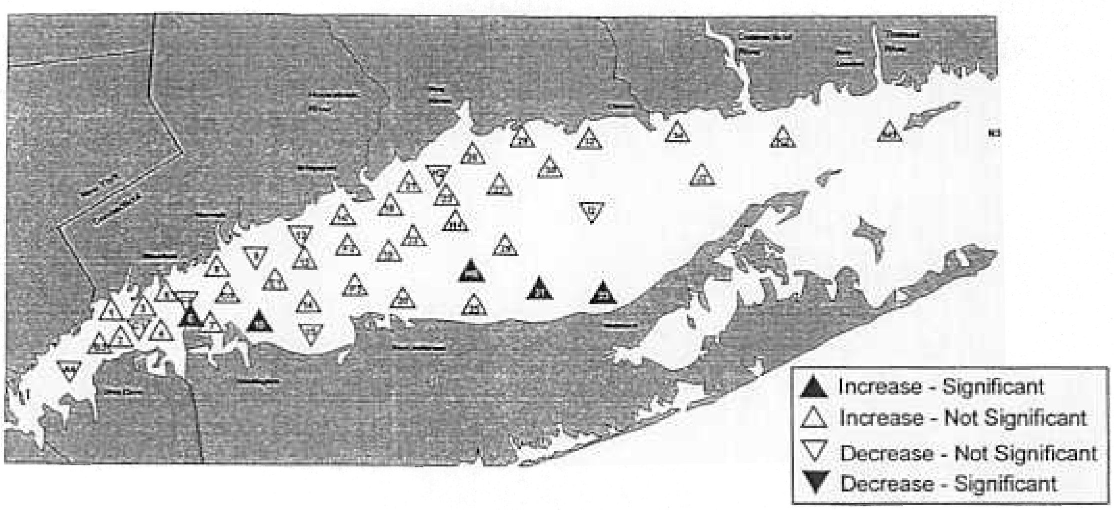

Figure 19. Trends in summertime bottom dissolved oxygen concentration at stations sampled over the five-year period of 1994 through 1998. No significant decreases in bottom water DO were observed.

Table 8. Results of trend analyses of summer bottom dissolved oxygen concentrations at fixed stations sampled from 1994-1998. Significant trends (p<0.05) are highlighted in grey.

				Linear Regression: Deseasonalized data is normally distributed			Seasonal Kendall's Test: Data not normally dist.
Station	Trend	Significant? (p<0.05)	p-value	R^2	Slope	Rate of Trend	Rate of Trend
A4	dec	No	0.7718	-	-	-	ns
B3	inc	No	0.8021	0.0021	8.14E-05	ns	-
C1	dec	No	0.3448	0.0407	-3.98E-04	ns	-
C2	dec	No	0.8705	0.0012	-7.03E-05	ns	-
D3	inc	No	0.2996	0.0370	1.77E-04	ns	-
09	dec	No	0.8414	-	-	-	ns
E1	inc	No	0.1717	0.0680	3.68E-04	ns	-
15	dec	No	0.6561	0.0072	-2.22E-04	ns	-
F2	inc	No	0.1281	0.0868	3.80E-04	ns	-
F3	inc	No	0.2629	0.0480	2.28E-04	ns	-
H2	dec	No	0.8728	-	-	-	ns
H4	inc	No	0.3672	0.0302	2.00E-04	ns	-
H6	**INC**	**Yes**	**0.0106**	**0.2341**	**5.92E-04**	**0.22 mg/L/yr**	-
I2	dec	No	0.7872	-	-	-	ns
J2	inc	No	0.0836	-	-	-	ns
K2	inc	No	0.5962	-	-	-	ns
M3	inc	No	0.0536	-	-	-	ns
N3	---	No	1.0000	-	-	-	ns
01	inc	No	0.0650	0.1092	4.96E-04	ns	-
02	inc	No	0.8624	0.0011	5.01E-05	ns	-
03	inc	No	0.2970	0.0362	2.48E-04	ns	-
04	inc	No	0.2340	-	-	-	ns
05	inc	No	0.5170	0.0151	2.07E-04	ns	-
06	**INC**	**Yes**	**0.0090**	**0.2428**	**8.65E-04**	**0.32 mg/L/yr**	-
07	inc	No	0.2224	-	-	-	ns
08	inc	No	0.3192	0.0431	3.59E-04	ns	-
10	**INC**	**Yes**	**0.0012**	**0.3578**	**8.55E-04**	**0.31 mg/L/yr**	-
12	dec	No	0.9684	0.0001	-1.40E-05	ns	-
13	inc	No	0.1750	0.0820	3.89E-04	ns	-
14	inc	No	0.0702	-	-	-	ns
16	inc	No	0.0918	0.1017	6.32E-04	ns	-
18	inc	No	0.1114	0.1022	5.54E-04	ns	-
19	inc	No	0.0536	-	-	-	ns
20	inc	No	0.1082	0.1238	4.69E-04	ns	-
21	inc	No	0.1587	0.0923	4.46E-04	ns	-
22	inc	No	0.0892	-	-	-	ns
23	inc	No	0.2011	0.0891	2.86E-04	ns	-
25	inc	No	0.5112	0.0231	2.21E-04	ns	-
26	inc	No	0.1487	0.0885	5.77E-04	ns	-
27	inc	No	0.0930	-	-	-	ns
28	inc	No	0.2997	0.0511	2.25E-04	ns	-
29	inc	No	0.2656	0.0646	3.63E-04	ns	-
30	inc	No	0.1738	-	-	-	ns
31	**INC**	**Yes**	**0.0423**	**0.1608**	**5.42E-04**	**0.20 mg/L/yr**	-
32	inc	No	0.0802	-	-	-	ns
33	**INC**	**Yes**	**0.0025**	**0.3343**	**6.92E-04**	**0.25 mg/L/yr**	-
34	inc	No	0.1010	-	-	-	ns
36	**---**	**No**	**Insufficient data**				

stations had increasing DO trends that were not significant ($p>0.05$). Only eight stations showed a decreasing DO trend, and none was significant ($p>0.05$). The eight stations that showed a declining trend in DO concentration, albeit insignificant, were spread throughout the Narrows and Western and Central Basins (stations A4, C1, C2, 09,12, 15, H2 and I2). The five stations that showed a significant increase in DO concentrations over the five year period were spread throughout the Sound: one in the Narrows, one in the Western Basin, two in the Central Basin, and one in the Eastern Basin (Table 8 and Figure 19). The summer of 1994 had the most severe hypoxic event of the five years included in the trend analysis. Since 1994 is at the beginning of the time period analyzed it would clearly affect the trend observed, especially at those stations that typically do not experience very low DO concentrations so that the widespread event of 1994 brought about unusually low DO concentrations. Station 33 in the Eastern Basin provides a good example; 1994 was the only year that the DO at this station was observed to fall below 3.0 mg/L.

There are additional data available from stations sampled since 1991. Year round bottom water dissolved oxygen data, from stations B3, D3 and F3, 1991-1997, have been evaluated using the same trend analysis technique as described above. The results of these analyses (reported separately in Program's Monthly Water Quality Monitoring data report, in draft) reveal increasing trends in bottom water DO at stations D3 (significant, $p=0.024$), F3 (significant, $p=0.005$), and B3 (not significant, $p=0.053$). From the review of these additional results, it is concluded that the trends seen in the 1994-1998 data need not be wholly attributed to the fact that 1994 was a particularly severe year for hypoxia. The longer-term data set supports the increasing trend seen at these three stations over the 1994-1998 period.

Weather Patterns and Hypoxia

We have already discussed the relationship between thermal stratification, specifically ΔTmax, and the area of hypoxia (see *Stratification* section). It is both long and short-term weather patterns that affect water temperatures and determine ΔT at any given time. In 1994, for example, a very cold winter resulted in the lowest winter water temperatures of the eight-year study (Table 9). With very cold bottom water temperatures, slow to warm, and surface water temperatures pushed higher

Table 9. Water temperature and hypoxic area summary data from Station D3. 1994 (bold) had the lowest and highest water temperatures recorded, tied for the highest ΔTmax, and had the largest area of hypoxia. See Figures 11 and 15.

Year	Minimum Winter Temp (C)	Maximum Summer Temp (C)	Maximum ΔT (C)	Maximum Area of Hypoxia (km^2)
1991	2.69	22.23	4.75	330
1992	1.86	20.89	4.83	224
1993	1.06	22.68	5.33	518
1994	**-0.68**	**24.08**	**6.33**	**1022**
1995	0.95	23.78	6.33	790
1996	-0.19	23.78	5.91	569
1997	1.87	21.81	4.96	77
1998	3.40	23.20	5.22	436

by a record early June heat wave, the largest ΔT (tied with 1995) of the eight years resulted (Station D3, see Figure 17; Table 9). The highest surface water temperature was also recorded that summer, so it is not surprising that 1994 had the most severe hypoxic event of the eight years (Table 6 and Figure 11d).

The three years with the lowest winter water temperatures, the highest summer water temperatures, and the largest ΔTmax (1994, 1995 and 1996) are also the three years with the largest areas of hypoxia (Table 9). We have already seen a strong relationship between ΔTmax and the maximum area of hypoxia (R^2=0.83; Figure 18). The data also revealed relationships between the area of hypoxia and the annual extreme water temperatures (Figure 20). Higher summer water temperatures (maximum summer water temperatures occur in surface waters) and lower winter water temperatures were both related to larger areas of hypoxia. These relationships were likely due to affects on ΔT and ΔTmax and the strength of stratification that resulted. Clearly the weather patterns that determined water temperatures in the Sound had an important influence on the extent of hypoxia.

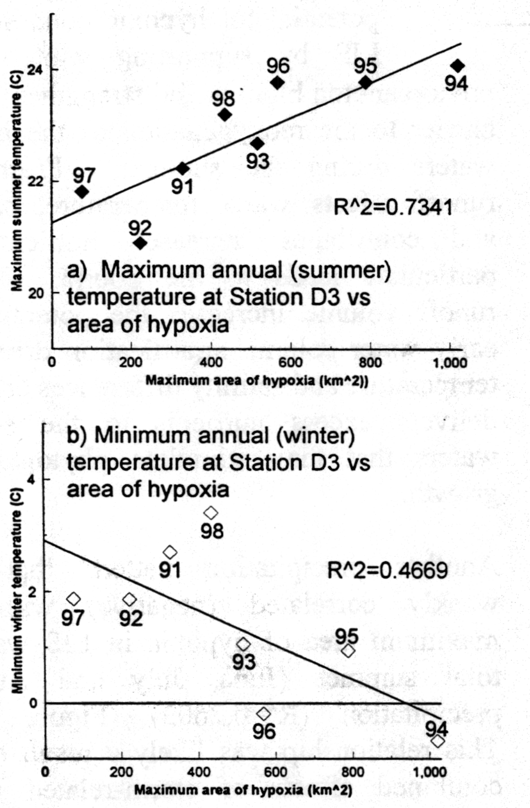

Figure 20. Relationship between a) maximum and b) minimum annual temperatures at Station D3 and the maximum area of hypoxia, 1991-1998.

Analyses of additional weather data revealed possible relationships between the hypoxia event and precipitation patterns. Winter precipitation (Figure 21) was defined as the total January, February and March precipitation. Summer precipitation (Figure 23) was defined as the total June, July and August precipitation. Duration and area both appear to be related to weather patterns and events, however these relationships seem independent of each other. Monthly precipitation data collected by the National Weather Service at Sikorsky Airport in Bridgeport, Connecticut were compared with hypoxia patterns. The sum of January, February and March precipitation correlated somewhat with the duration and area (Figure 22).

The duration of hypoxia in LIS was correlated with winter precipitation (January to March) during the period of study (R^2=0.4291) (Figure 22a). The three years with the longest duration of hypoxia (1993, 1994 and 1998) also had the highest precipitation totals for these three months and these monthly precipitation totals were greater than the 1950-1981 median precipitation (Figure 21).

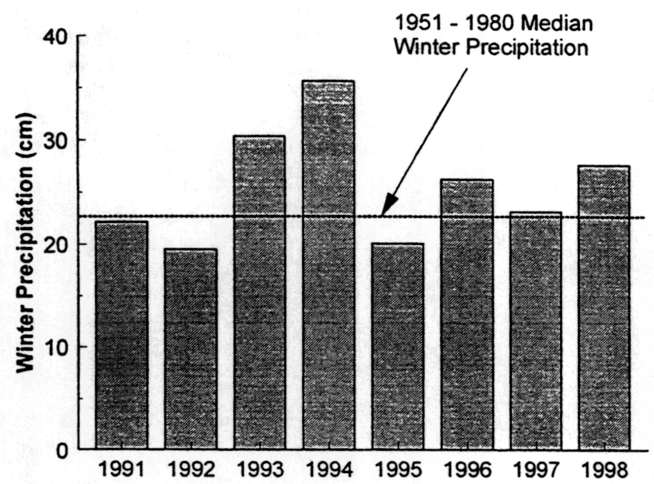

Figure 21. Winter precipitation (January through March) totals for the years 1991-1998. 30-year median precipitation data from Hunter and Meade, 1983.

The maximum area of hypoxia also showed a slight correlation with winter precipitation totals (R^2=0.3479) (Figure 22b). 1994, the year with the largest area of hypoxia was also the year with the highest January - March precipitation.

Increased winter precipitation appeared to contribute to lower summer dissolved oxygen concentrations in LIS. Increased winter/spring runoff likely resulted in higher nutrient loading and stronger stratification of the water column. Both factors raised the potential for hypoxic conditions in LIS by supporting winter/spring phytoplankton blooms and strengthening the barrier to the reoxygenation of the bottom waters during the summer. Freshwater runoff affects water temperature, salinity and contributes increased nutrient and particulate loads to the Sound. Larger runoff volume increases the potential for early water column stratification driven by temperature and salinity differences and also delivers excess nutrients to the surface waters that may stimulate phytoplankton growth.

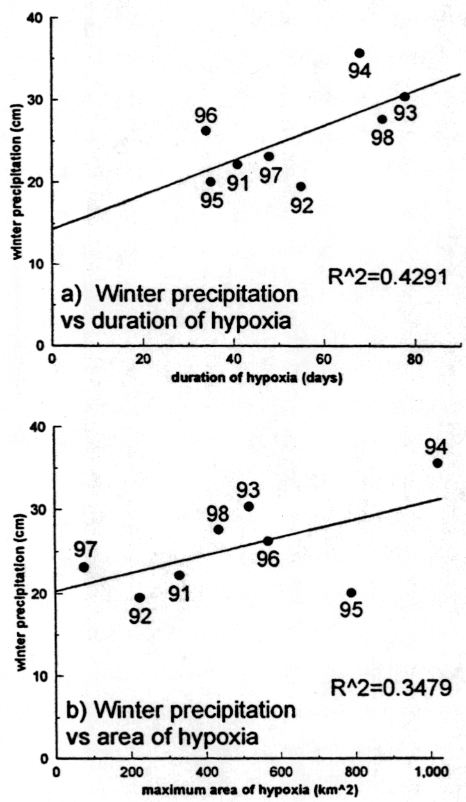

Figure 22. Relationship between winter precipitation (January through March total) and the a) duration and b) maximum area of hypoxia, 1991-1998.

Another precipitation pattern that was weakly correlated (negative) with the maximum area of hypoxia in LIS was the total summer (June, July and August) precipitation (R^2=0.2603) (Figure 24a). This relationship was likely a result of the combined effects of storm-related wind-induced mixing and mixing caused by storm-induced runoff that was colder than the surface waters. Summer rainfall and accompanying winds have the potential to weaken stratification allowing some mixing of the water column and oxygenation of the water column below the pycnocline.

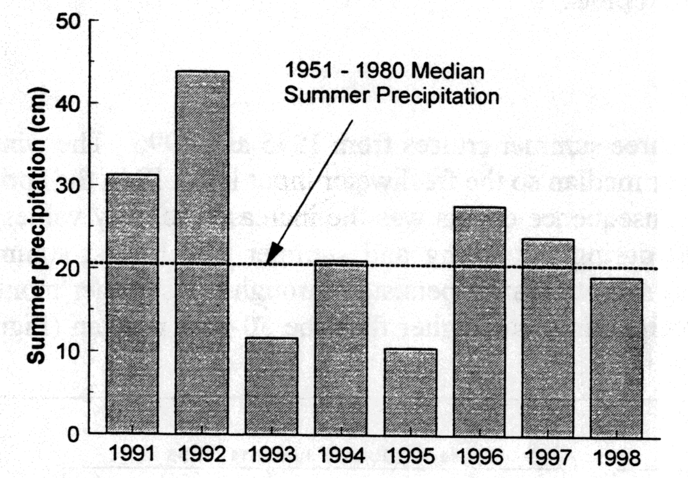

Figure 23. Summer precipitation (June through August) totals for the years 1991-1998. 30-year median precipitation data from Hunter and Meade, 1983.

Summer precipitation did not correlate with the duration (R^2=0.0591) or date of onset (R^2=0.0574) of hypoxia. Since hypoxia typically begins in July (only in 1996 was an August start observed), June and July precipitation was evaluated for any relationship to the date of onset of hypoxia. Total June and July precipitation correlated somewhat to the date of onset of hypoxia, with increased precipitation during these months contributing to a later onset date (R^2=0.3291) (Figure 24b). Mixing of the water column during these months had the potential to temporarily weaken or break up the stratification. Weakening of the water column stratification led to delayed onset, reduced area, or lessened severity of hypoxia.

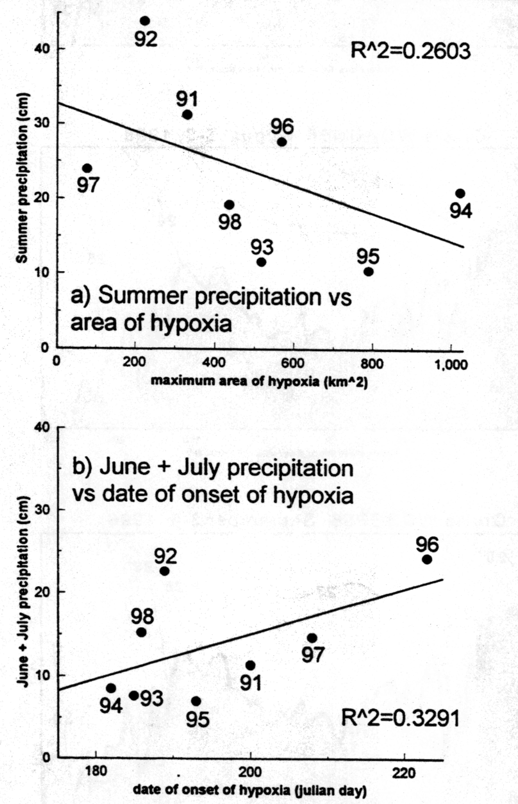

Figure 24. Relationship between a) summer precipitation and the maximum area of hypoxia; and b) June + July precipitation and the date of onset of hypoxia, 1991-1998.

Increased summer precipitation appeared to contribute to improved summer dissolved oxygen concentrations in LIS through its effects on water column mixing. Water column mixing was promoted by an increase in freshwater runoff and winds associated with storm events. Increased water column mixing interrupted the development of water column stratification, delaying the development and persistence of hypoxia.

Axial Profiles

Temperature and salinity distributions from west to east along the deep water axial transect of LIS (Figure 5) provide a useful means of reviewing data for cruise-to-cruise or year-to-year comparisons. Variations in water column distributions of temperature and salinity attributed to varying weather patterns, for example, could be easily evaluated.

Following are some examples of distribution plots.

Salinity

Figure 25 shows salinity distributions for three summer cruises from 1995 and 1996. The winter precipitation in 1995 was below the 30-year median so the freshwater input into LIS in the spring was less than in other years. One main consequence of this was the increased salinity values in the Sound. With continued low rainfall during the spring and summer (the lowest summer precipitation of the eight years) the higher salinity waters persisted through the summer months (Figure 25). In contrast, 1996 winter precipitation was higher than the 30-year median (Figure

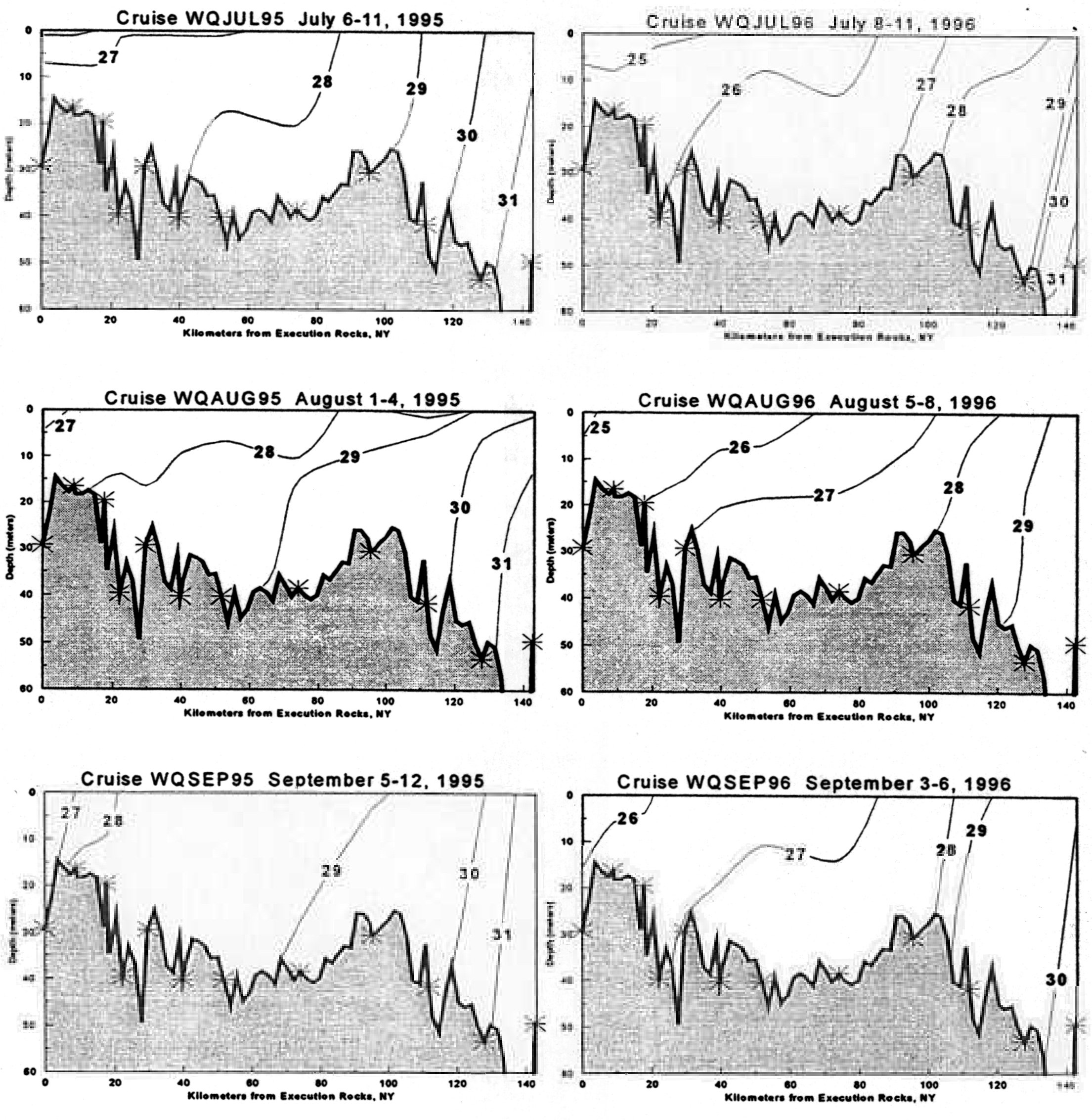

Figure 25. Salinity distribution from west to east (Execution Rocks, Station A4 to Fisher's Island/The Race, Station M3) along the deep water axial transect through Long Island Sound during WQJUL, WQAUG, and WQSEP cruises, 1995 and 1996. "*" indicates location of stations for which data are plotted.

21), providing larger freshwater runoff volume and lower salinity throughout the Sound (Figure 25). In addition, 1996 summer precipitation was greater than the 30-year median (Figure 23) (in fact, 1996 had the highest June+July precipitation of the eight years), so that continued freshwater inputs kept salinity values low through the summer.

Temperature

Figure 26 shows temperature distributions for three summer cruises from 1995 and 1996. Unlike the salinity distributions, the temperature distributions for these two years are fairly similar. Using data from Station D3 as an example, we can see that these two years had very similar

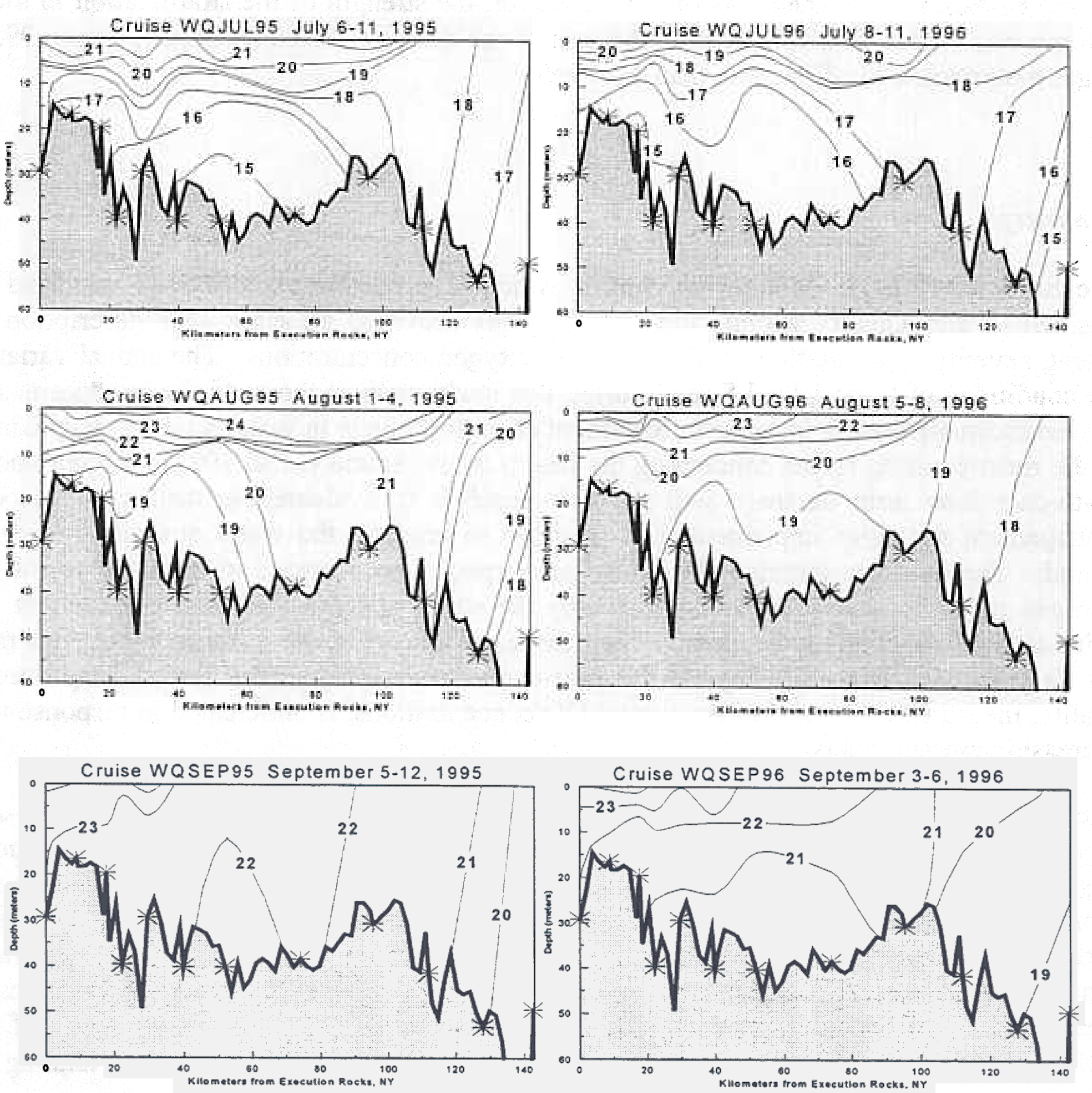

Figure 26. Temperature distribution from west to east (Execution Rocks, Station A4 to Fisher's Island/The Race, Station M3) along the deep water axial transect through Long Island Sound during WQJUL, WQAUG, and WQSEP cruises, 1995 and 1996. "*" indicates location of stations for which data are plotted.

temperature patterns. Both started out with very similar low winter water temperatures (the second and third lowest after 1994) of 0.95 (1995) and –0.19 (1996) degrees C. Similarly, these two years had identical high summer water temperatures, at 23.8 degrees C. The higher summer precipitation in 1996 (Figure 23) is likely the cause of the slightly cooler surface water temperatures in that year.

As mentioned previously, the stratification in the Sound is primarily a function of temperature. In Figure 26, we can see that the difference between the surface and bottom water temperatures during the WQJUL and WQAUG cruises was generally larger in 1995 than in 1996 (as was seen for Station D3 in Figure 17). In addition, we can see in the WQAUG95 profile (Figure 26) isotherms that are very close together. Both of these pieces of information are consistent with a stronger thermocline (and, therefore, a stronger pycnocline) and a stronger barrier to the vertical mixing of dissolved oxygen. As discussed earlier, the strength of the stratification in the water column was related to a difference in the area of the Sound affected by hypoxia, and 1995 had a larger maximum area of hypoxia than did 1996

Summary

The Summer Hypoxia Monitoring Survey which is part of the broader Long Island Sound Ambient Water Quality Monitoring Program, has provided an eight year description of the extent, severity, and duration of low dissolved oxygen concentrations. The annual variations in the conditions of Long Island Sound during this study support the need for the continuation of the monitoring program in order to document changing trends in water quality. Hypoxia is one of the most pressing issues concerning the health of the Sound (LISS 1994). A continuous and up-to-date long term database will make it possible to evaluate the results and success of management strategies implemented in an effort to improve the water quality of Long Island Sound. The nutrients entering the Sound are expected to decrease in response to the phased nitrogen reduction strategies implemented by the states of New York and Connecticut. Some point source reductions have already been made. Although these nitrogen reductions may not yet be positively detectable beyond the year-to-year variability in the system, improved water quality, measured as a trend of increasing DO concentrations, is anticipated in response to these decreasing nutrient loads.

The current sampling design, which was initiated in 1994, provides excellent station-specific time series of DO concentrations and gives a good Sound-wide representation of conditions. In this report, the DO trend analyses are based on five years of data and the apparent trends may be short-term phenomena. Continued data collection and analysis efforts will enhance our understanding of the trends in DO conditions. The apparent increasing trend in bottom water DO concentrations, the cyclic pattern in the duration of hypoxia, and the annual fluctuations in the area affected will be interpreted more accurately as we are able to remove effects of natural variations and focus on the effects of management efforts to reduce nutrient loading to the Sound.

Review of Descriptive and Significant Findings

During the period 1991-1998:

- Many patterns observed concerning DO concentrations in LIS were consistent from year to year; typically, the Narrows showed the lowest mean bottom water DO concentration with DO increasing eastward
- Hypoxia (DO less than 3.0 mg/L) was observed every year during the month of August; five of the eight years during July; and five of the eight years during September
- The maximum area of hypoxia (DO of 3.0 mg/L or less) generally occurred during August
- The average hypoxic event (1991-1998) began on July 15th, ended on September 6th , lasted 54 days, and covered a maximum area of 494 km^2, 18% of the study area
- There appeared to be some relationship between the date of onset of hypoxia and its duration: a late onset seemed to affect a shorter duration
- DO concentrations less than 2.0 mg/L were observed every year; DO less than 1.0 mg/L were observed in five of the eight years
- Five stations showed a significant increase in bottom water DO based on trend analysis of 1994-1998 data; no stations showed significantly decreasing DO
- Stratification strength and timing was very important to the development and eventual extent of hypoxia: when thermal stratification was strong during the early summer, the area of hypoxia that developed later in the summer was large
- Weather patterns and events were also very important, such as annual high and low air temperatures, precipitation, runoff volume and timing, wind events and other physical factors as they influenced stratification and water column mixing in the Sound

This work was partially funded by the United States Environmental Protection Agency's Long Island Sound Study. Questions regarding this report and requests for additional data or information from the Long Island Sound Ambient Water Quality Monitoring Program should be brought to the attention of the Planning and Standards Division of the Bureau of Water Management.

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